

## (12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization  
International Bureau(43) International Publication Date  
31 July 2003 (31.07.2003)

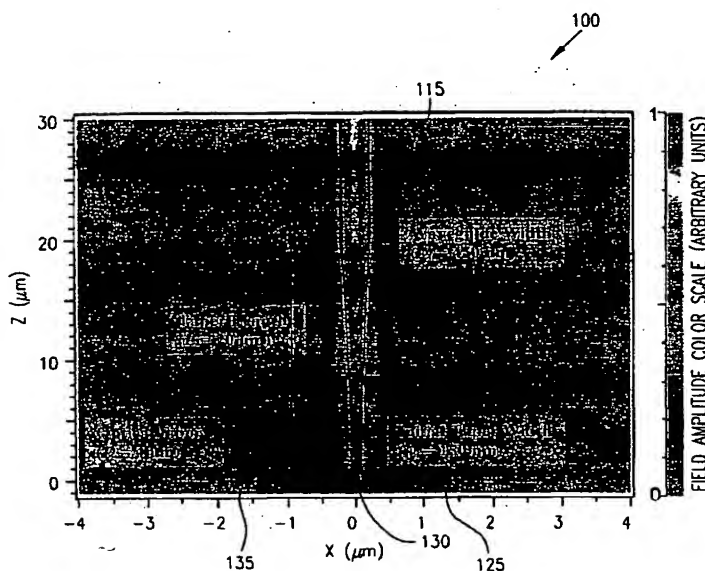
PCT

(10) International Publication Number  
WO 03/062883 A2

- (51) International Patent Classification<sup>7</sup>: G02B 6/26 [BR/US]; 2417 Hasbrouck Apts., Ithaca, NY 14850-2645 (US).
- (21) International Application Number: PCT/US03/01608
- (22) International Filing Date: 17 January 2003 (17.01.2003)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:  
60/350,294 17 January 2002 (17.01.2002) US  
60/375,959 25 April 2002 (25.04.2002) US  
60/382,686 22 May 2002 (22.05.2002) US  
60/382,676 22 May 2002 (22.05.2002) US
- (71) Applicant: CORNELL RESEARCH FOUNDATION, INC. [US/US]; 20 Thornwood Drive, Suite 105, Ithaca, NY 14850 (US).
- (71) Applicants and  
(72) Inventors: LIPSON, Mark [BR/US]; 8 Muriel Street, Ithaca, NY 14853 (US). DE ALMEIDA, Vilson, Rosa
- (74) Agents: STEFFEY, Charles, E, et al.; Schwegman, Lundberg, Woessner & Kluth, P.O. Box 2938, Minneapolis, MN 55402 (US).
- (81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW.
- (84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: HIGH-INDEX CONTRAST WAVEGUIDE COUPLER



(57) Abstract: An optical coupler comprises an optical tip having a small cross section. The coupler is tapered from a waveguide width to the small cross section tip. In one embodiment, the length of the taper is approximately 40 μm long. The waveguide width is approximately 450 nm wide, and the tip is approximately 150 x 250 nm wide. The tip couples to an optical fiber, which in one embodiment is approximately 4 μm wide. In a further embodiment, the waveguide tapers into a combination of multiple tips to provide a better overlap between a mode profile of the fiber and the coupler.

WO 03/062883 A2



**Published:**

— without international search report and to be republished upon receipt of that report

*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

## **High-Index Contrast Waveguide Coupler**

### **Field of the Invention**

The present invention relates to waveguide couplers, and in particular to  
5 a tapered high-index contrast waveguide coupler.

### **Background of the Invention**

An optical fiber is usually formed of a core of dielectric material have an index of refraction slightly higher than that of cladding surrounding the core.  
10 Typical optical fibers are forms of SiO<sub>2</sub>. Integrated optical circuit optical waveguides are usually smaller, consisting of a dielectric film. They are useful for interfacing with sub-micron size nanophotonic structures. Optical waveguides have been difficult to connect to fibers due to index and mode mismatch between the fiber and waveguide. Prior attempts at coupling involved  
15 long structures that are difficult to fabricate, or convert only the mode size.

### **Summary of the Invention**

An optical coupler comprises an optical tip having a small cross section. The coupler is tapered from a waveguide width to the small cross section tip. In  
20 one embodiment, the length of the taper is approximately 40  $\mu\text{m}$  long. The waveguide width is approximately 450 nm wide, and the tip is approximately 150 x 250 nm wide. The tip couples to an optical fiber, which in one embodiment is approximately 4  $\mu\text{m}$  wide.

In a further embodiment, the waveguide tapers into a combination of  
25 multiple tips to provide a better overlap between a mode profile of the fiber and the coupler.

### **Brief Description of the Drawings**

- FIG. 1 is a cross section of an optical coupler in accordance with the  
30 present invention.  
FIG. 2 is a cross section of a tip of the optical coupler of FIG. 1.  
FIG. 3 is a cross section of tips of a multi-tip optical coupler.  
FIG. 4 is a perspective view of a single and multiple tip optical couplers.

- FIG. 5 is a cross section representation of an xy mode field profile of a single tip optical coupler.
- FIG. 6 is a graph of mode mismatch losses dependent on tip width for the coupler of FIG. 5.
- 5 FIG. 7 is a graph of mode mismatch losses due to misalignment between the tip and an optical fiber.
- FIG. 8 is a graph showing mismatch loss dependence on tip width for double-tip optical couplers.
- FIG. 9 is a perspective view of a thin waveguide coupled segmented  
10 vertical waveguide
- FIG. 10 is a perspective view of one example of a planar optical waveguide having thin waveguide coupled waveguide segments.
- FIG. 11 is a perspective view of a further example of a planar optical waveguide having thin waveguide coupled waveguide segments.
- 15

### **Detailed Description of the Invention**

The following description and the drawings illustrate specific embodiments of the invention sufficiently to enable those skilled in the art to practice it. Other embodiments may incorporate structural, and other changes.

20 Examples merely typify possible variations. Individual components and functions are optional unless explicitly required, and the sequence of operations may vary. Portions and features of some embodiments may be included in or substituted for those of others. The scope of the invention encompasses the full ambit of the claims and all available equivalents. The following description is,

25 therefore, not to be taken in a limited sense, and the scope of the present invention is defined by the appended claims.

A waveguide incorporating an optical coupler is shown at 100 in FIG. 1, including an xz cross-section of electric field profile at  $y = 0$ . The waveguide comprises a waveguide section 115, a tapered section 120, and a tip 125 having  
30 an end 130 coupled to an optical fiber 135. In one embodiment, the waveguide 115 is a high-index contrast waveguide. The tapered section 120 is based on high-index contrast materials, such as Si and SiO<sub>2</sub> or other III-V semiconductor materials having optical waveguide properties.

In one embodiment, the tip has a cross section of less than 250 nm for Si-SiO<sub>2</sub>, and approximately 150 nm in one embodiment. The tip couples directly to the optical fiber 135, which has a diameter of approximately 4  $\mu$ m in one embodiment. The tip may be positioned directly adjacent the fiber, or may be  
5 adhered to the fiber in one of many known ways such that the tip is approximately centered on an end of the fiber. If not precisely centered, efficiency may decrease, but some amount of light coupling still occurs.

The tapered section 120 has a length of approximately 40  $\mu$ m in one embodiment; increasing in width from the tip to the waveguide to approximately  
10 450 nm. The taper provides matching of the mode of the tip to the waveguide mode. With the tapered section 120 at approximately 40  $\mu$ m, both the mode profile and the effective index were converted. For the Si-SiO<sub>2</sub>, waveguide, the size of the waveguide is approximately 450 x 250 nm. The waveguiding material is Si, and the cladding is SiO<sub>2</sub>. Other high-index contrast materials may  
15 also be used, such as (any pair of materials that have a high index contrast – Si and SiO<sub>2</sub> well known characteristics and easy to process.

The principle of operation of the coupler relies on a low-confined approach. Using a very narrow optical tip, much smaller than the wavelength of light, the field in the cross-section perpendicular to the propagation in the xy  
20 plane, is predominantly evanescent. In other words, most of the optical power is spread in the cladding region, instead of in the core. This induces a very large mode profile, of the order of an optical fiber mode. The structures efficiently couple light with fibers with very low losses, even though the mode profile at the tip is not Gaussian, but mostly exponentially decaying.

Si waveguides have been shown to transmit light at a wavelength,  $\lambda$ , of  
25 approximately 1.5  $\mu$ m with very low losses. Using high-contrast materials allows miniaturization of the coupler, and presents a low index mismatch with a fiber, since most of the field resides in the SiO<sub>2</sub> region of the tip 130, causing the effective index to be close to that of the SiO<sub>2</sub>. Reflections are also  
30 negligible.

Many fabrications methods are available to form the structure of FIG. 1. Some processes include reactive ion etching, reactive ion beam etching, N<sub>2</sub> ion milling and others. Certain photolithography methods may also be used to form

the taper and tip. Given the submicron structures, electron beam lithography offers high spatial resolutions. Tapers may also be formed by epitaxial growth.

The coupling efficiency for the structure of FIG. 1 is believed to correspond to about 60%. This is approximately equal to the overlap between the fiber and the tip mode profile (66%). The small discrepancy arises due to losses in the taper. FIG. 2 is a cross section of the mode profile of the tip 130. The dimensions of the tip are approximately 100 x 150 nm, and the fiber core 135 has a diameter of approximately 4  $\mu$ m. The dimensions may be varied significantly to accommodate different desired performances, and different wavelengths of radiation.

In order to further increase efficiency, a combination of multiple tips is used as seen in FIG. 3. A better overlap between the mode profile of the fiber and the coupler is achieved. The mode profile of a two tip device is shown in FIG. 3. A first tip 310 is positioned from a second tip 320 to create an overlap of the mode profile of the two tips with the fiber mode profile of approximately 92%. The distance between the two tips adjacent the fiber 330 is significantly less than the diameter of the optical fiber.

Further, in one embodiment, each tip has a height greater than a width, and the heights of the two fibers are substantially parallel and equally spaced from the longitudinal center of the fiber or waveguide. The two tips create a substantially circular mode profile at the intersection with the fiber or waveguide. In the embodiment shown, the two tips are positioned such that the circular mode profile is substantially concentric with the longitudinal axis of the fiber. Embodiments with more than two tips are also within the scope of the invention.

In one embodiment, the waveguide is coupled to optical circuitry formed on an integrated circuit, such as a substrate on which the waveguide is formed. The waveguide tapers as described, and couples directly to an optical fiber for carrying light to other integrated circuits on different substrates, or for longer transmission as desired.

A perspective view of a single taper and double taper waveguide coupler 405 and 410 respectively are shown in FIG. 4. The basic building block of the structures is based on a short taper 415 with nanometer-size tip 420 composed of the same high-index contrast material that composes the waveguide 405. The

refractive index of the cladding material 425 and 428 is chosen to be very close to the effective index of the optical fiber mode. The tip 420 having a width  $w_s$  is followed by the taper 415 of length  $l_s$  to the width of the waveguide  $w_w$ . The height  $h$  of the waveguide, tip and taper is constant throughout the coupler in one embodiment. The coupler comprises a planar optical circuit. The double taper waveguide 410 has two tips 430 and 435, each one with width  $w_d$  separated by  $s_d$ . In one embodiment, the tapers join at the waveguide at a greater width,  $s_d + w_d$ , and then taper back to the width of the waveguide for a taper length of  $l_{d2}$ . In some embodiments, the tapers are linear, and in others they follow a curved form, such as parabolic.

The tapers can present any geometry (linear, quadratic, cubic, exponential, etc.), but usually the linear is not the most efficient one. One method of manufacturing the couplers utilizes purchased Silicon-On-Insulator (SOI) wafers, followed by patterning of the Si structures and then deposit of SiO<sub>2</sub>. Any other combination of materials that can lead to high index contrast, like Si ( $n = 3.48$ ) and SiO<sub>2</sub> ( $n = 1.46$ ), and are appropriate to micro/nanofabrication can be used.

The coupler is believed to operate based on the fact that the field in the narrow optical tip is predominantly evanescent. This induces a very large mode field, of the order of the optical fiber mode field diameter (MFD). This delocalization of the mode field profile increases the overlap with the optical fiber mode. In addition, most of the mode field resides in the cladding region at the tip, causing the effective index to be close to that of the fiber, which makes back-reflections become negligible. The taper converts both the mode profile and the effective index in a typical range of tens of microns. In general, a rectangular tip cross-section will present a polarization dependent behavior, what can be suppressed by introducing a square tip cross-section. In one embodiment, the waveguide height is equal to the tip to result in a square tip cross-section. In a further embodiment, a vertical taper is provided from the waveguide height along the taper to the tip.

A square cross-section for achieving good power overlap with optical fiber is about 150 nm x 150 nm in one embodiment. With no vertical taper, the final waveguide will be somewhat about 450 nm x 150. In a further embodiment, the final waveguide has a cross-section 450 nm x 250 nm,

providing effective indexes of 2.51 (TE) and 2.05 (TM). Using multiple tips, the coupling efficiency is increased by improving the mode overlap of the coupler with the mode of the optical fiber.

Simulations were performed at  $\lambda = 1.55 \mu\text{m}$  for the TE-like polarization.

- 5 The single-mode optical fiber used as an input mode reference has a circular core of diameter  $d = 4 \mu\text{m}$ , with indices  $n_{\text{core}} = 1.48$ ,  $n_{\text{clad}} = 1.46$ , which gives a MFD of  $d_{\text{MFD}} = 4.9 \mu\text{m}$  and an effective index of 1.468. This corresponds to the MFD of a typical Erbium-doped optical fiber. Simulations were performed based on beam propagation method (BPM) and finite-difference time-domain (FDTD)
- 10 method. The waveguiding and cladding materials are Si ( $n_{\text{Si}} = 3.48$ ) and  $\text{SiO}_2$  ( $n_{\text{Si}} = 1.46$ ), respectively. The applicability of this approach is not limited only to these materials. The waveguide height and width are taken as  $h = 250 \text{ nm}$  and  $w_w = 450 \text{ nm}$ , respectively, in order to achieve single-mode operation.

- FIG. 5 shows a xy mode field profile of the single-tip structure in FIG. 4,
- 15 where  $w_s = 120 \text{ nm}$  (the width of the tip) at the tip facet, together with the fiber MFD and tip dimensions. The field is calculated using mode solvers based on semi-vector 3D-BPM. The mode field profile at the tip qualitatively matches the fiber MFD. The power overlap and thus the mode mismatch losses depend on the tip width as shown in FIG. 5. The maximum power overlap between the
  - 20 optical fiber and tip modes was about 94 %, obtained for  $w_s = 120 \text{ nm}$ . This corresponds to mode mismatch losses of 0.26 dB. In FIG. 6 it is seen that a margin of error of 28 nm in the fabrication process of the tip width can be tolerated for mode mismatch losses increase of only 0.5 dB with respect to the optimum performance. For all values of  $w_s$ , the effective index of the single-tip
  - 25 mode is below 1.48, leading to back-reflection losses at the facet better than 48 dB. FIG. 7 illustrates the mode mismatch losses due to misalignment between the single-tip structure and the optical fiber, along the x (solid line) and y (dashed line) directions. In order to stay within 1 dB of the minimum mode mismatch losses, a relatively large misalignment tolerance of  $1.2 \mu\text{m}$ , between
  - 30 fiber and tip, is allowed in both x and y directions (FIG. 7). In order to convert the mode at the tip facet into the waveguide mode, a tapered transition of length  $l_s = 30 \mu\text{m}$  is used by gradually varying both sidewalls in a symmetric parabolic transition towards the final waveguide width, where the parabola vertex is located at the tip. A qualitative picture of the propagating field, obtained using



semi-vector 3D-BPM, is shown in FIG. 8. One can see the strong field in the waveguide following the coupler, where some higher order waveguide modes are still present. Using 2D-FDTD losses were quantitatively assessed. This approach provides a good approximation of the losses of the 3D counterpart, since tapering is only done on the width (xz plane), whereas the height is kept constant. In one embodiment, the taper can effectively convert both mode size and effective index. In further embodiments, longer tapers and/or different taper transitions are used to minimize losses.

A double-tip coupler, as shown in FIG. 4 is used to further improve power overlap. In this structure one has a larger flexibility in shaping the mode field profile by adjusting both parameters  $s_d$  the width between tips 430 and 435, and  $w_d$ , the width of the tips 430 and 435. The xy mode field profile at the double-tip facet is shown in FIG. 6 for  $s_d = 1.1 \mu\text{m}$  and  $w_d = 105 \text{ nm}$ . The maximum power overlap between the optical fiber and tip modes was about 96.4 % (mode mismatch losses of 0.16 dB), obtained for  $s_d = 1.1 \mu\text{m}$  and  $w_d = 105 \text{ nm}$ . FIG. 7 shows the dependence of the mode mismatch losses on a few geometric parameters. The tolerance to the tip width is increased with  $s_d$ . For all values of  $s_d$  and  $w_d$ , the effective index of the double-tip mode is below 1.47, leading to back-reflection losses at the facet better than 51 dB.

FIG. 8 shows a plot of simulated mode mismatch losses versus tip width for the two tip taper of FIG. 4. Three spacings of the tips are shown for varying tip width. The tolerance to the tip width is increased with  $s_d$ . For all values  $s_d$  and  $w_d$ , the effective index of the double-tip mode is below 1.47, leading to back-reflection losses at the facet better than 51 dB.

A distributed Bragg reflector is shown generally at 910 in FIG 9. A waveguide having a high index of refraction has a first end 915, and several sections of approximately equal diameter 920, 925, and 930 positioned between the first end 915 of the waveguide and a second end of the waveguide 940. Section 920 is coupled to the first end 915 by a thin waveguide section 945. Section 920 and 925 are coupled by a thin waveguide 950. Section 925 and section 930 are coupled by a thin waveguide 950, and section 930 and second end 940 are coupled by a thin waveguide 960. Each thin waveguide has a high index of refraction. The waveguide structure, including the ends of the

waveguide, the sections, and thin waveguides are surrounded by medium 970 having a low index of refraction.

In one embodiment, the medium is air, having a index of refraction of 1. The waveguide structure is formed of silicon, and has an index of refraction of approximately 3.48. With one set of geometries, the effective indices of refraction are calculated at 3.27 and 1.45 in the high and low index regions respectively. Losses vary with the width of the thin waveguide, as does the reflectivity. Optimizing the width of the thin waveguide provides high reflectivity and low losses for a distributed Bragg reflector.

In one embodiment a thin waveguide section in combination with the medium having a low index of refraction form an optical coupler that propagates light. The medium having a low index of refraction is referred to as a thick elongate cladding portion. The thin waveguide section is referred to as a thin elongate material that is disposed within the cladding. The thin elongate material has a thickness smaller than the wavelength of the light to be propagated. In one embodiment, the optical coupler has a mode profile that is comparable in size to a mode profile of an optical fiber. The thin elongate material is formed of Si and the cladding is formed of SiO<sub>2</sub>. The thin elongate material has a sub micron cross section in one embodiment.

In a further embodiment, the optical coupler further comprises additional thin elongate materials disposed within the cladding having a high index of refraction, wherein the additional thin elongate material has a thickness substantially smaller than the wavelength of the light to be propagated. In one embodiment, the additional thin elongate materials are axially aligned with an axis of the cladding.

The thin elongate materials are separated from each other to minimize interference from light propagated by them.

In FIG.s 10 and 11, planar optical waveguides forming distributed Bragg reflectors are shown at 1010 and 1110. Reflector 1010 comprises waveguide sections 1015, 1020, 1030, 1040 and 1050 coupled by thin waveguides 1055, 1060, 1070 and 1080. In this case, the wires are substantially centered on each waveguide section, and have much smaller widths and heights than the waveguide sections. They are essentially floating between the sections at the geometric center of the cross section of such sections.

In Figure 11, reflector 1110 comprises waveguide sections 1115, 1120, 1125, 1130, and 1135 coupled by thin waveguides 1140, 1150, 1160 and 1170. In both the waveguides, the indices of refraction for the waveguide sections and wires are high compared to medium surrounding them. The thin waveguides in  
5 this embodiment are the same height as the waveguide sections, but are much narrower. They are easily formed using a single photolithograph step to define both the waveguide sections and the thin waveguides.

The planar optical waveguides are formed on a substrate or buffer of a material with lower refractive index. The waveguides are buried in a material  
10 with lower refractive index or left with air as the upper layer. Fabrication is performed using lithographic processes (optical or e-beam) for patterning the device onto the substrate, such as silicon on insulator substrates, or another appropriate bulk or buffered substrate. Following patterning, reactive ion etching or appropriate deposition processes, depending on the type of substrate  
15 utilized, are performed to complete the device. The devices may be performed in many different manners, as the resulting structure and difference in index of refraction in surrounding medium are easily obtainable by many different processes, including those yet to be developed.

The vertical structure of FIG. 9 is formed by epitaxial growth or  
20 deposition using any process, such as MBE, CVD, MOCVD, evaporation and sputtering, as well as any other available process. Materials used are usually III-V compounds and alloys, as well as oxides thereof, but other materials may also be used. Conventional processes used for fabricating reflectors in vertical cavity surface emitting lasers are inherently appropriate for fabrication of the vertical  
25 structures. In a very conventional process, MBE is used for epitaxially growing or alternate GaAs and AlAs layers, (optical or e-beam) lithography is used for patterning the cross sectional regions, and plasma or reactive ion etching is employed for transferring the pattern. Using this example, selective etching of AlAs with respect to GaAs layers is performed as a final step in order to obtain  
30 the corresponding narrow AlAs thin waveguide layers alternated by wide high-index GaAs layers. This leads to a structure geometrically similar to that of FIG. 9, which presents a generally cylindrical cross section, although other cross section shapes may also be used.

In a further embodiment, an optical type fiber having embedded one or more thin waveguide structures made with a different index of refraction material than the surrounding fiber. The thin waveguide structures could be located towards the middle of the optical-type fiber or around the periphery. In one embodiment, each thin waveguide carries a separate optical signal. The thin waveguides are spaced from each other such that signals carried on the separate thin waveguide structures would not interfere with each other nor would there be a significant loss of signal from the thin waveguide. The application of this is for telecommunications and perhaps in any optical system where simultaneous transmission of multiple separate optical signals are desired - such as an optical equivalent of multiwire cables used in computers now (for use in an optical computer). One method of making such fibers comprises arranging high and low index fibers and heating and drawing them a thin fiber of substantially parallel fibers.

15

### Conclusion

A new class of easy-to-manufacture, micron-sized devices allows coupling between an optical fiber and a high-index contrast waveguide, with low losses. The structures are composed of high index contrast materials, and consist of one or multiple nanometer-size tips tapered to the waveguide dimensions. The structures are based on Si/SiO<sub>2</sub> in a 30  $\mu$ m long device. The ease of manufacture stems from the fact that only lateral tapering is necessary, making it widely suitable for few-step fabrication processes with conventional e-beam lithography. Losses of the couplers are governed mainly by the power overlap between the field at the tip(s) facet(s) and the fiber mode. One can then envision the losses to become negligible by increasing this overlap using geometries that employ several tips. This class of on-chip devices are very small and different embodiments are capable of high coupling efficiency, extremely low back-reflections, and ease of manufacture.

25

**Claims**

1. An optical coupler comprising:  
an optical tip;  
a waveguide; and  
5 a tapered section between the optical tip and the waveguide having a cladding of a material having a low index of refraction, and wherein the optical tip, waveguide and tapered section have a high index of refraction.
2. The optical coupler of claim 1 wherein the waveguide is formed of Si and  
10 the cladding is formed of SiO<sub>2</sub>.
3. The optical coupler of claim 1 wherein the tapered section is approximately 40um in length.
- 15 4. The optical coupler of claim 1 wherein the width of the optical tip is substantially less than the wavelength of light to be transferred through the optical tip.
5. The optical coupler of claim 1 wherein the tip is coupled to an optical  
20 fiber.
6. The optical coupler of claim 5 wherein the optical tip has sub micron cross section, and the optical fiber has a diameter greater than a micron.
- 25 7. The optical coupler of claim 5 wherein the optical tip is approximately 100 x 250 nm, and the optical fiber has a diameter of approximately 4 um.
8. An optical coupler comprising:  
a waveguide having a core with a tapered section extending into an  
30 optical tip, the waveguide having a cladding about the core formed of a material having a low index of refraction, and wherein the core including the tapered section and tip have a high index of refraction relative to the cladding.

9. The optical coupler of claim 8 wherein the core is formed of Si, and the cladding is formed of SiO<sub>2</sub>.
10. The optical coupler of claim 9 wherein the effective index at the tip of the waveguide is close to that of SiO<sub>2</sub>.
11. The optical coupler of claim 8 wherein the cross section of the tip is much smaller than the wavelength of light in the waveguide.
12. The optical coupler of claim 8 wherein optical power is spread in the cladding region proximate the optical tip.
13. The optical coupler of claim 8 wherein a mode profile at the tip of the waveguide approximately matches an optical fiber mode to which it may couple.
14. An optical coupler comprising:  
a waveguide having a core with a tapered section extending into two optical tips, the waveguide having a cladding about the core formed of a material having a low index of refraction, and wherein the core including the tapered section and tips have a high index of refraction relative to the cladding.
15. The optical coupler of claim 14 wherein the core is formed of Si, and the cladding is formed of SiO<sub>2</sub>.
16. The optical coupler of claim 15 wherein the effective index at the tips of the waveguide is close to that of SiO<sub>2</sub>.
17. The optical coupler of claim 14 wherein the cross section of the tips is much smaller than the wavelength of light in the waveguide.
18. The optical coupler of claim 14 wherein optical power is spread in the cladding region proximate the optical tips.

19. The optical coupler of claim 14 wherein a mode profile at the tips of the waveguide is large, on the order of an optical fiber mode.
20. The optical coupler of claim 19 wherein the modes overlap by  
5 approximately 92%.
21. The optical coupler of claim 14 wherein the tips each comprise a height greater than a width, and wherein the two heights are oriented substantially parallel to each other, and concentric from each other with respect to the  
10 longitudinal axis of the waveguide.
22. The optical coupler of claim 21 wherein the two tips create a substantially circular mode profile at the intersection with the waveguide.
- 15 23. An optical circuit comprising:  
a waveguide having a core with a tapered section extending into an optical tip, the waveguide having a cladding about the core formed of a material having a low index of refraction, and wherein the core including the tapered section and tip have a high index of refraction relative to the cladding; and  
20 an optical fiber having one end coupled to the tip at approximately the longitudinal center of the optical fiber.
24. The optical circuit of claim 24 wherein the optical fiber has a diameter of approximately 4  $\mu\text{m}$ , the tip has a cross section of approximately 150 x 150 nm, the taper has a length of approximately 40  $\mu\text{m}$ , and the waveguide has a width of  
25 approximately 450 nm.
25. An optical coupler that propagates light comprising:  
a thick elongate cladding portion having a low index of refraction; and  
30 a thin elongate material disposed within the cladding having a high index of refraction, wherein the thin elongate material has a thickness smaller than the wavelength of the light to be propagated.

26. The optical coupler of claim 25 wherein the optical coupler has a mode profile that is comparable in size to a mode profile of an optical fiber.
27. The optical coupler of claim 25 wherein the thin elongate material is  
5 formed of Si and the cladding is formed of SiO<sub>2</sub>.
28. The optical coupler of claim 25 wherein the thin elongate material has a sub micron cross section.
- 10 29. The optical coupler of claim 25 and further comprising an additional thin elongate material disposed within the cladding having a high index of refraction, wherein the additional thin elongate material has a thickness substantially smaller than the wavelength of the light to be propagated.
- 15 30. The optical coupler of claim 25 and further comprising plural additional thin elongate materials disposed within the cladding having a high index of refraction, wherein the additional thin elongate materials have a thickness substantially smaller than the wavelength of the light to be propagated.
- 20 31. The optical coupler of claim 30 wherein the thin elongate materials are separated from each other to minimize interference from light propagated by them.



1/10

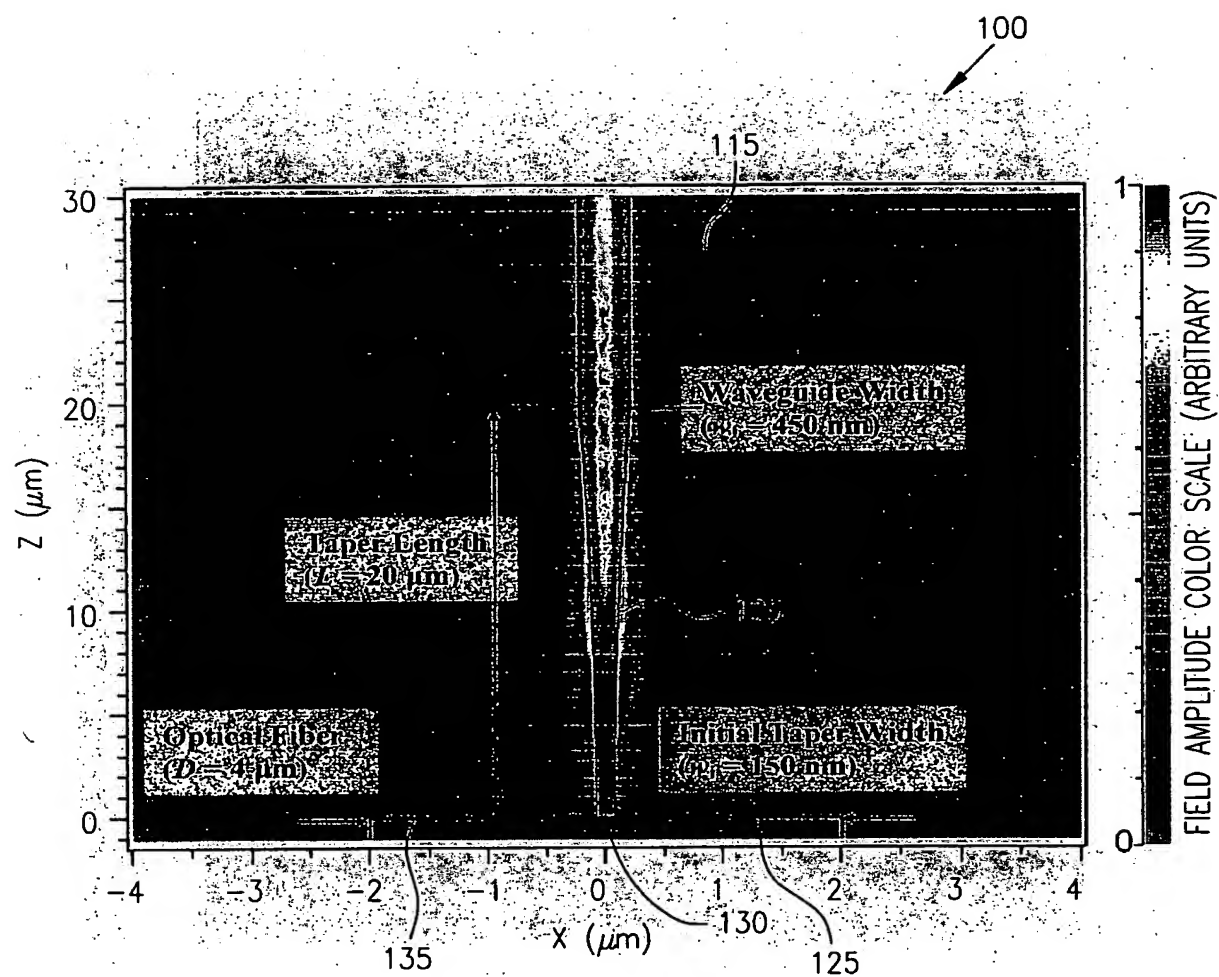


FIG. 1

2/10

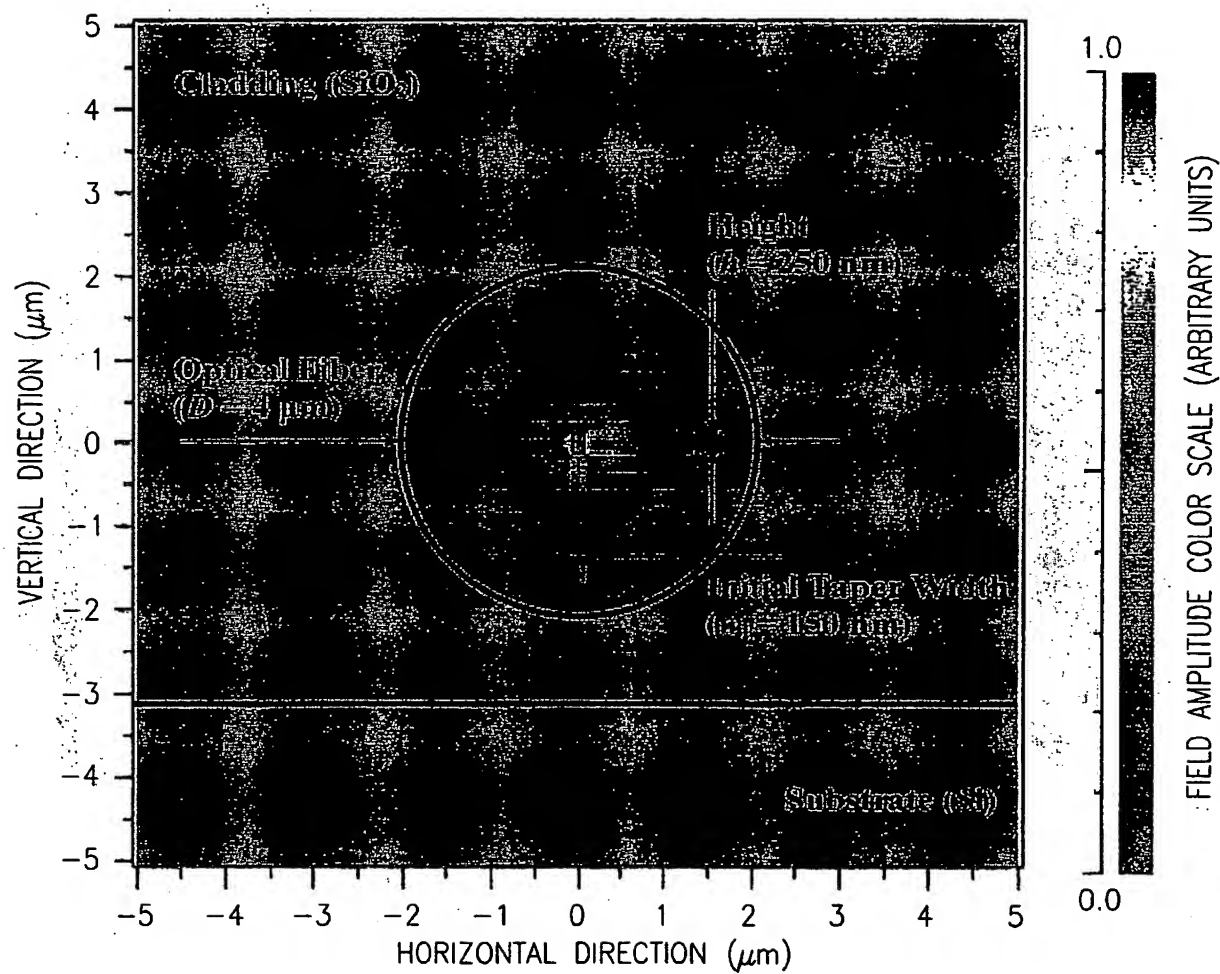


FIG. 2

3/10

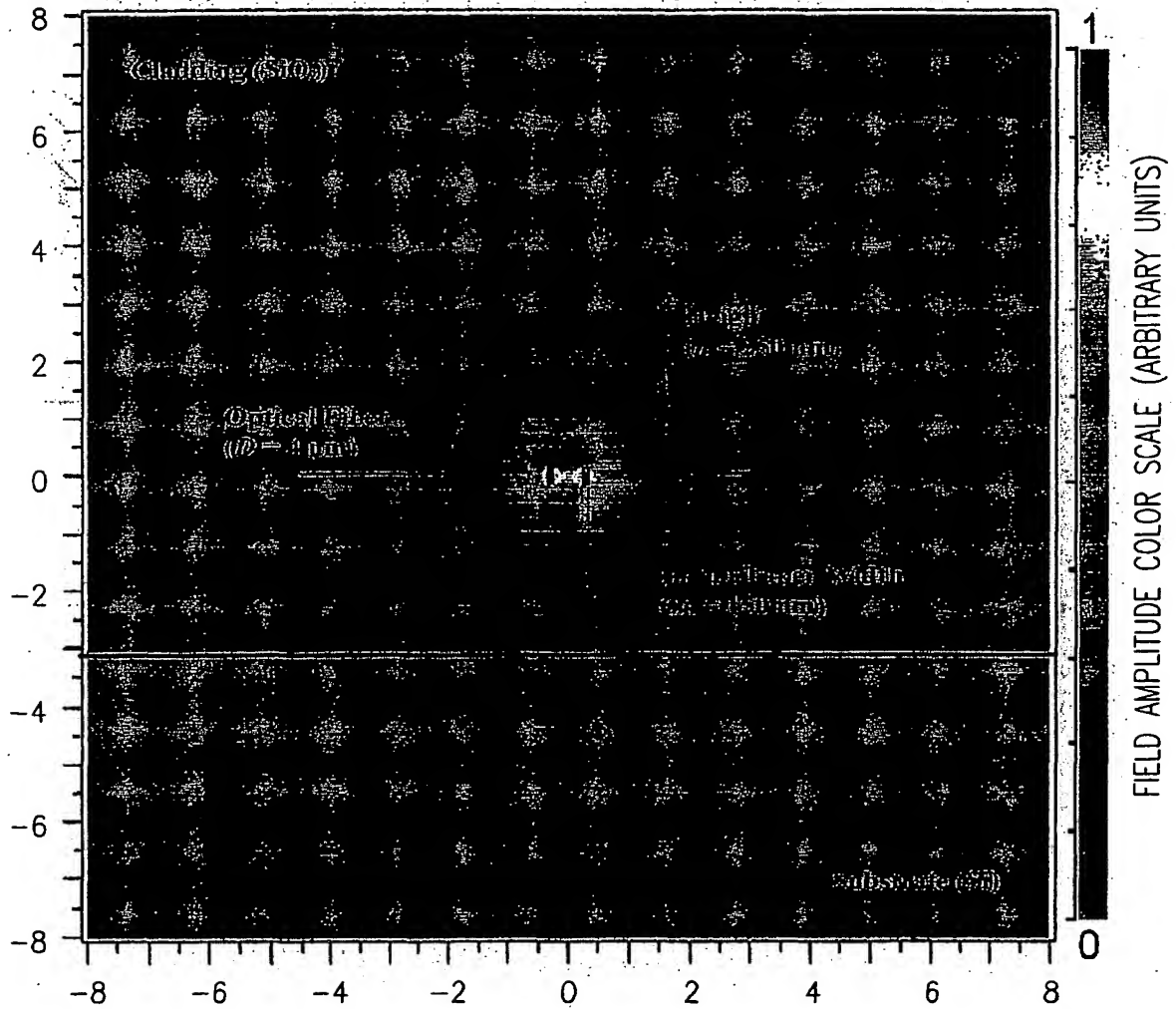


FIG. 3

4/10

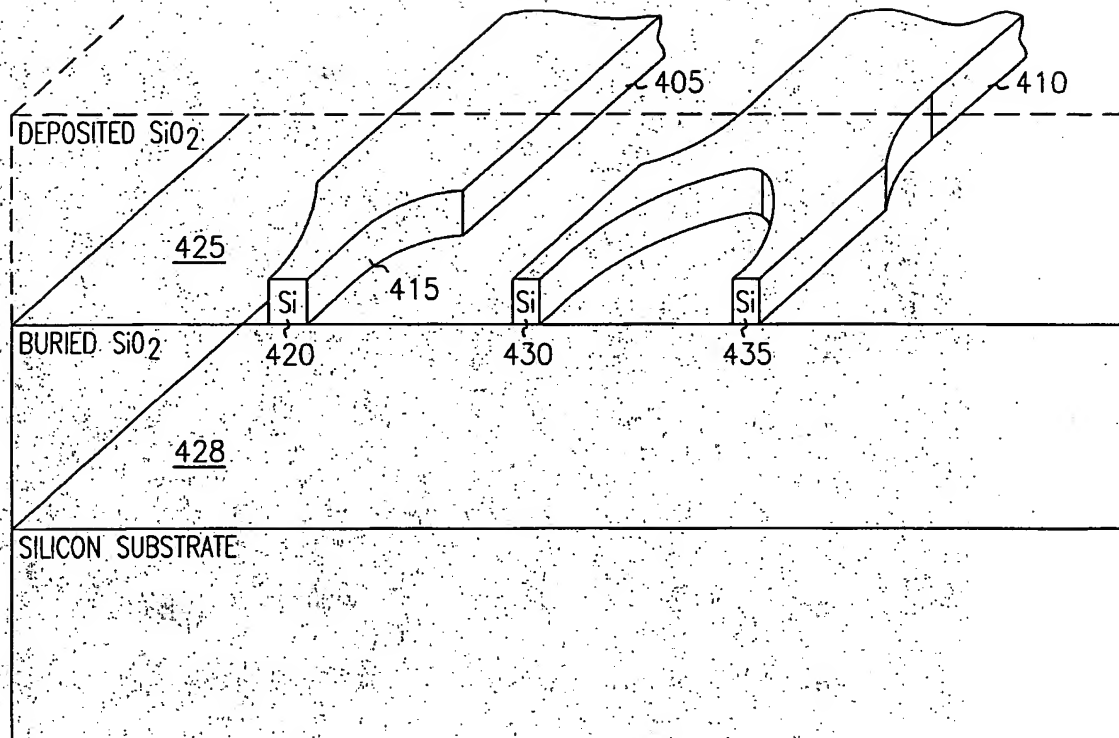


FIG. 4

5/10

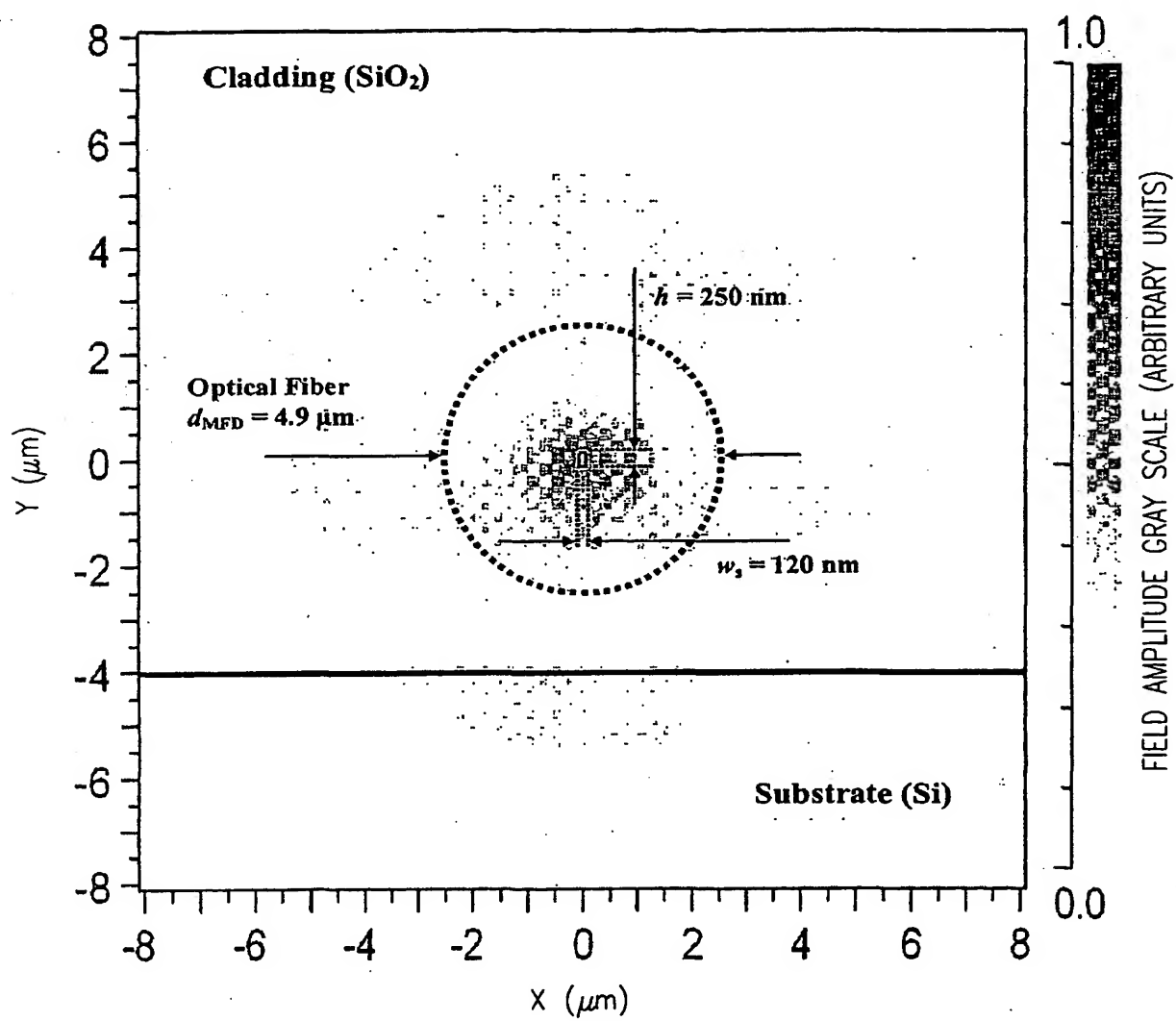


FIG. 5

6/10

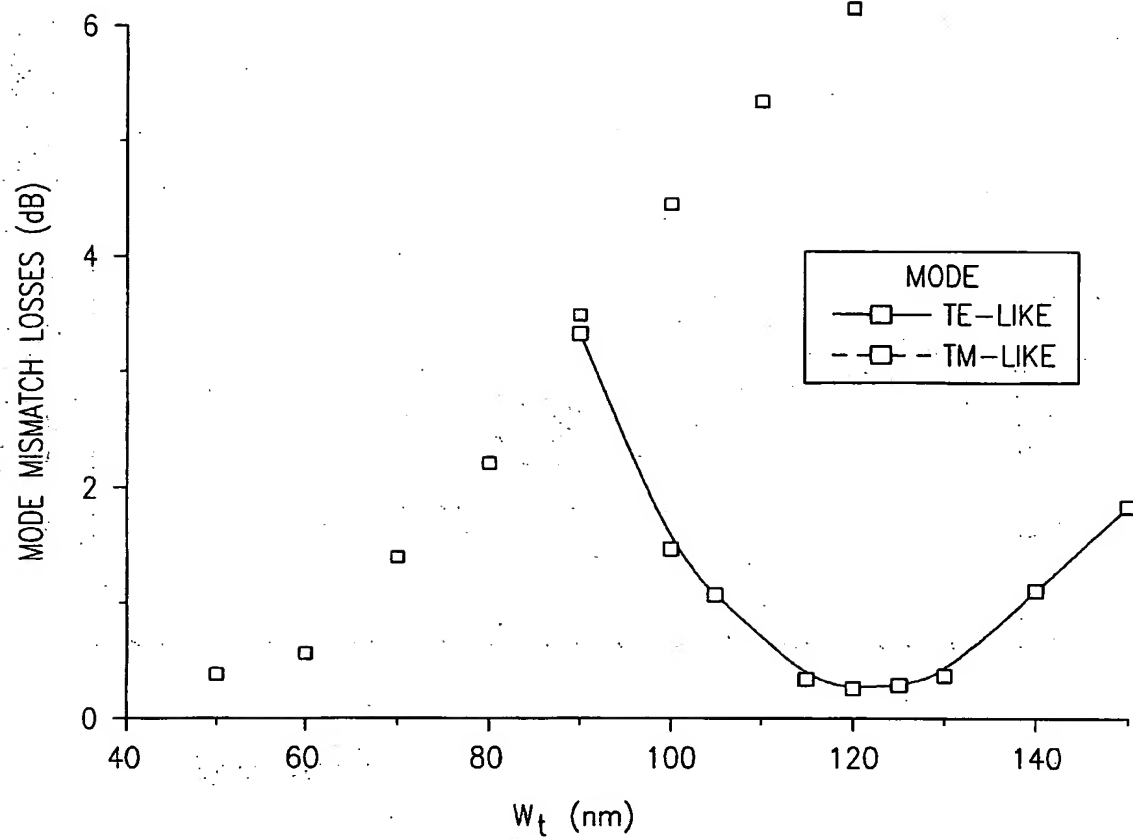


FIG. 6

7/10

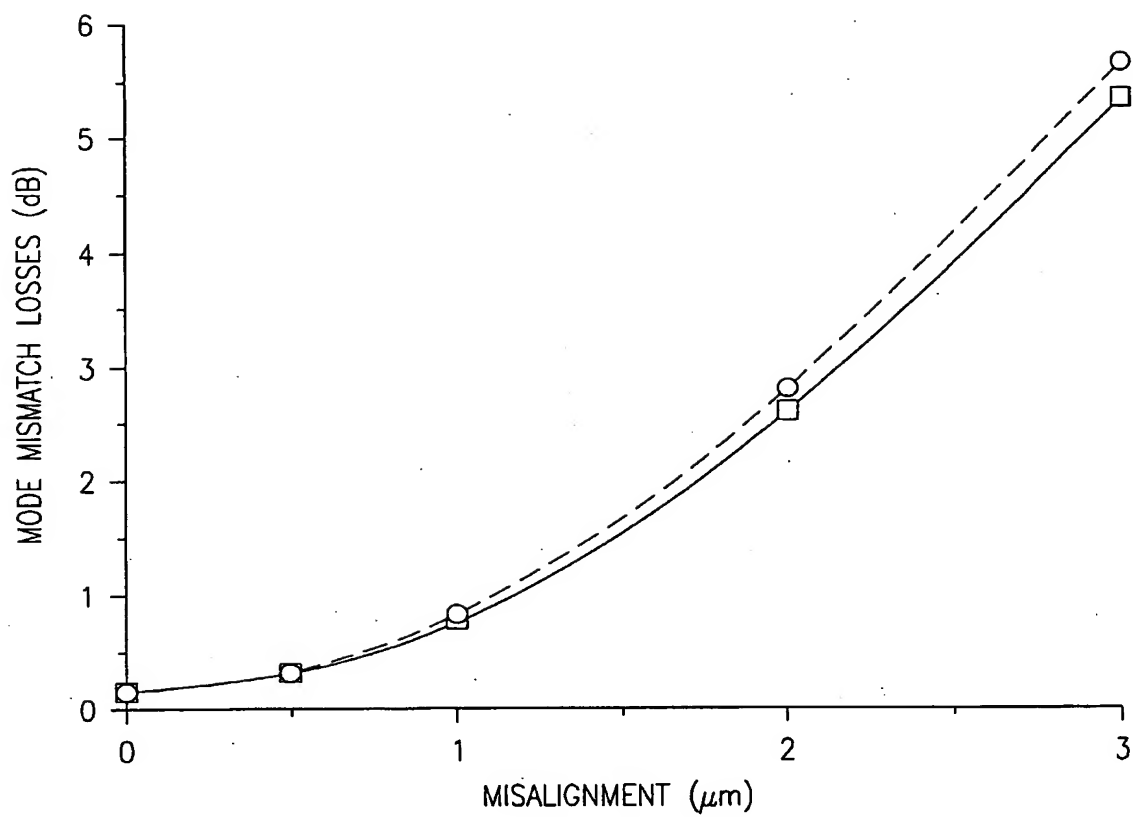


FIG. 7

8/10

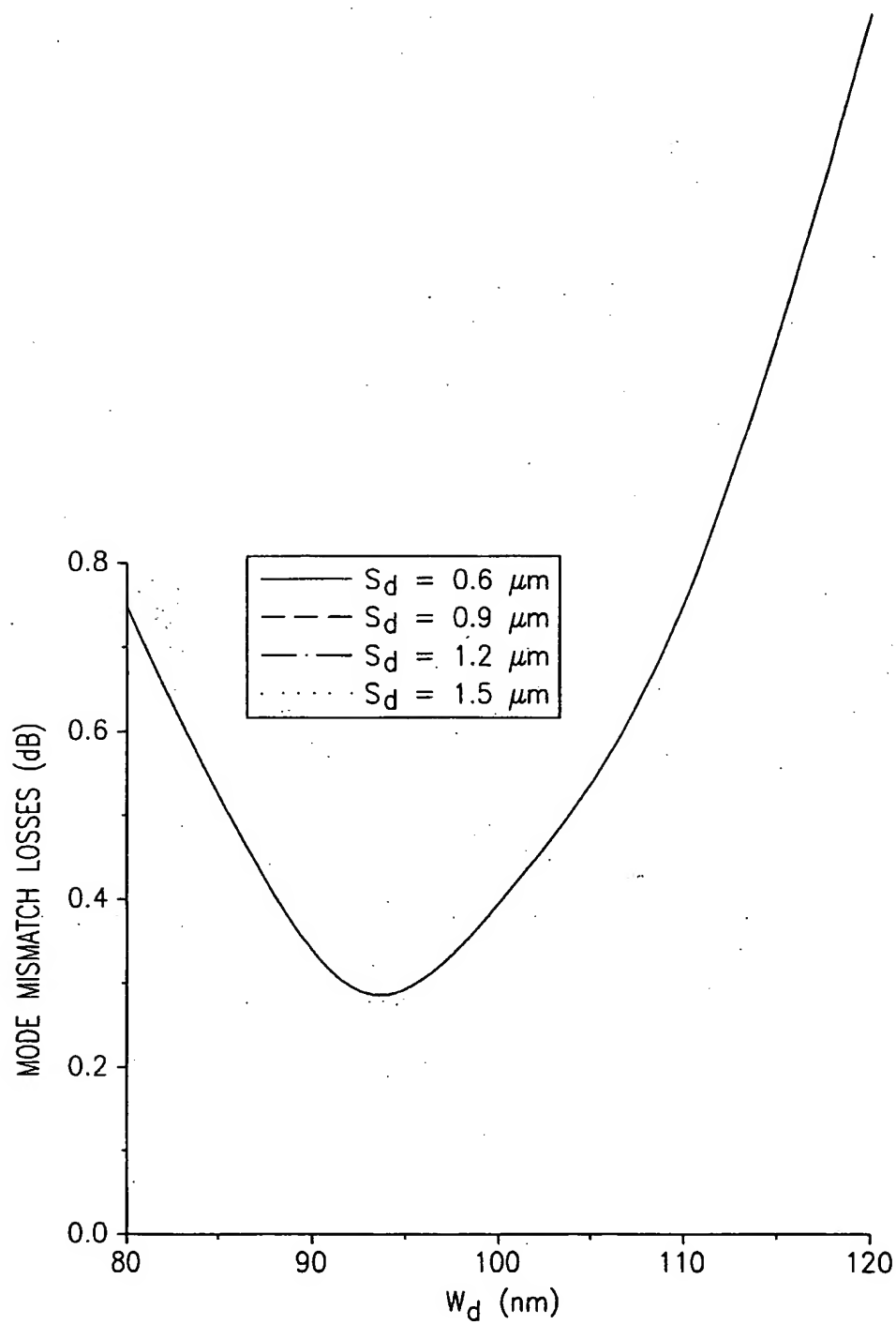


FIG. 8



9/10

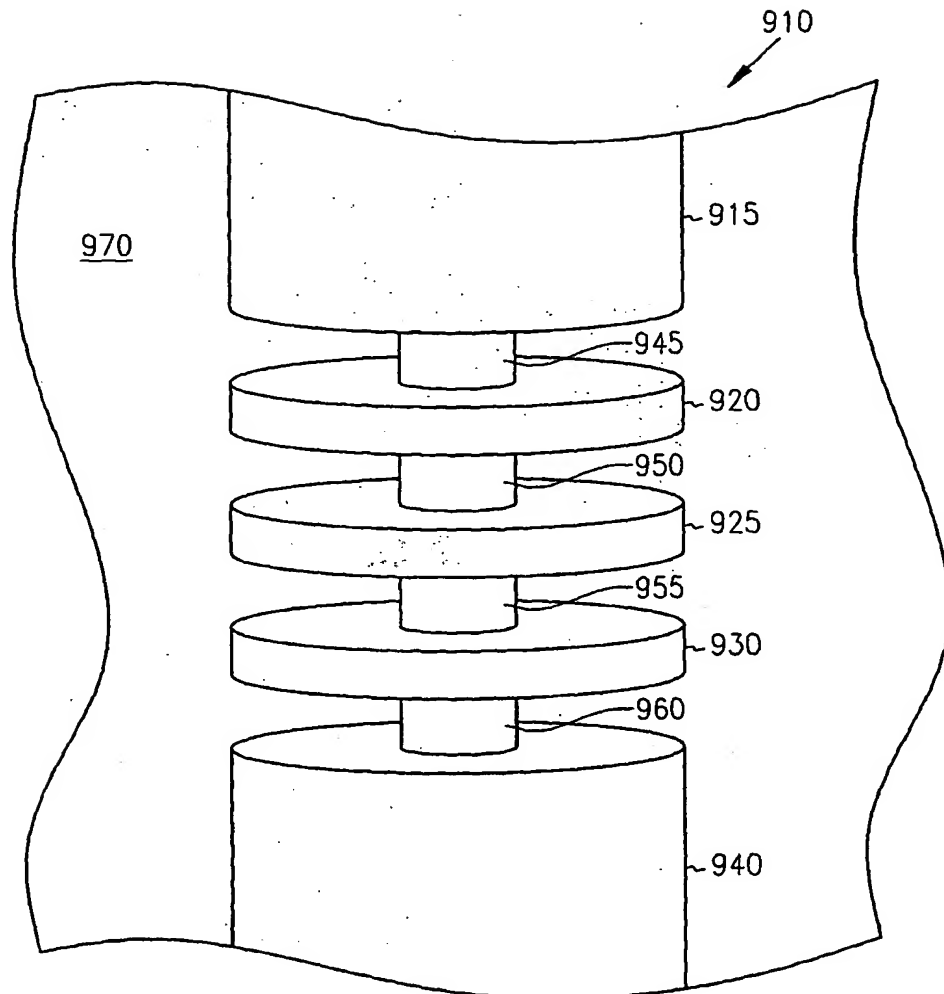


FIG. 9

10/10

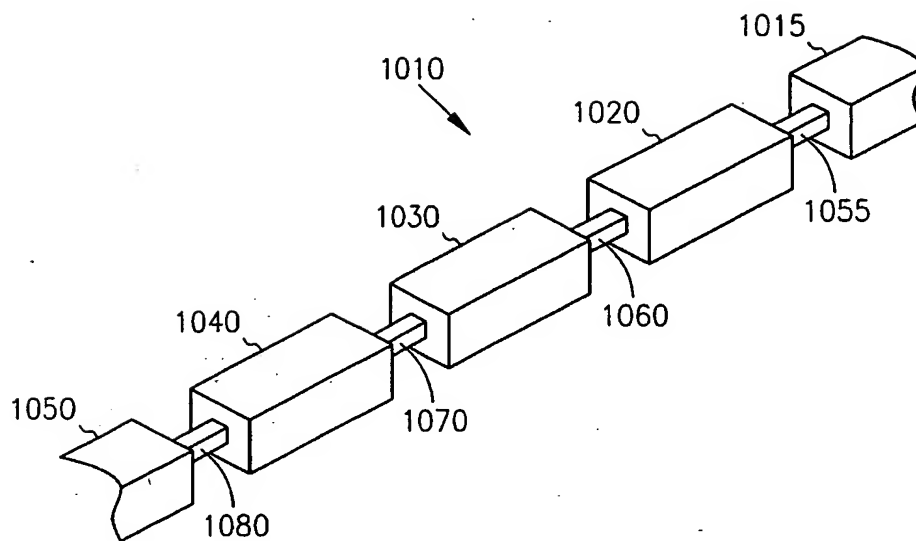


FIG. 10

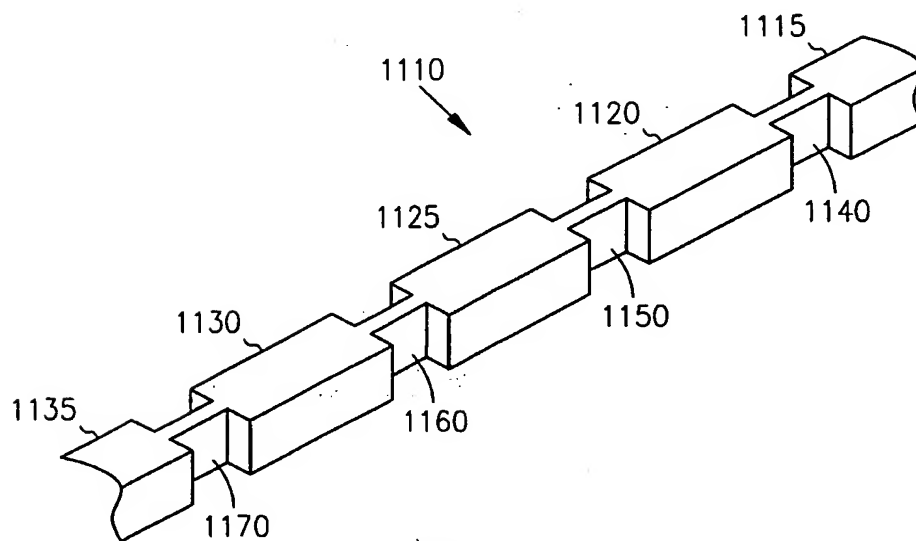


FIG. 11

**This Page is Inserted by IFW Indexing and Scanning  
Operations and is not part of the Official Record.**

## **BEST AVAILABLE IMAGES**

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

☒ **BLACK BORDERS**

☒ **IMAGE CUT OFF AT TOP, BOTTOM OR SIDES**

☐ **FADED TEXT OR DRAWING**

☒ **BLURRED OR ILLEGIBLE TEXT OR DRAWING**

☐ **SKEWED/SLANTED IMAGES**

☒ **COLOR OR BLACK AND WHITE PHOTOGRAPHS**

☐ **GRAY SCALE DOCUMENTS**

☐ **LINES OR MARKS ON ORIGINAL DOCUMENT**

☐ **REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY**

☐ **OTHER:** \_\_\_\_\_

**IMAGES ARE BEST AVAILABLE COPY.**

**As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.**